TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 472

EXPERIMENTS WITH A WING FROM WHICH THE BOUNDARY LAYER IS REMOVED BY PRESSURE OR SUCTION

By K. Wieland

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E R R A T A*

Page 4, bottom: Change "$g = 981g \times cm/s^2$" to

$g = 981 \times cm/s^2$

Page 7, near top: Change "air density = 0.00117g" to

air density $\rho = 0.00117/g$

(Unfortunately g = acceleration due to gravity and g = gram cannot be distinguished.)

Page 11, top: Change "W_d and W_p" to

W_d and W_r

(The $w^2 \times 10^6$ are the squares of the w values of Table III, but expressed im $(cm/s)^2$.

*Published in Zeitschrift für Flugtechnik und Motorluftschiffahrt, January 18, 1927, p. 407.

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EXPERIMENTS WITH A WING FROM WHICH THE BOUNDARY LAYER IS REMOVED BY PRESSURE OR SUCTION.*

By K. Wieland.

This account of the experiments performed during the summer of 1925 in the physical laboratory of Basel University (Section for Applied Mechanics) constitutes only a progressive report, as the investigations are yet far from being finished. The reason for publishing a report now is that there is some question regarding the immediate continuation of the work.

Object of the Investigation

With an unsymmetrical wing and a rotating Magnus cylinder, the lift is produced by the superposition of parallel and circulatory flows. According to Kutta-Joukowsky the mathematical expression for the lift A reads

$$A = \rho \Gamma v$$

in which ρ denotes the air density, Γ the circulation, and v the velocity of the parallel flow.

According to W. Thompson

$$\Gamma = \oint c \, ds$$

*"Untersuchungen an einem neuartigen Düsenflügel," Zeitschrift für Flugtechnik und Motorluftschiffahrt, August 16, 1927, pp. 346-350.

in which c denotes the circulatory velocity on a closed curve (s) around the wing.

An explanation of the circulatory flow is furnished by the boundary-layer theory of Prandtl and the consequent vortex formation. Each vortex on leaving the trailing edge, calls forth a compensating circulatory motion (Fig. 1). It is obvious that a one-sided circulation can be produced only by an unsymmetrical vortex formation. (In Fig. 1 the lower vortex is the stronger one.)

According to this explanation, it must evidently be possible to increase the circulation either by increasing the size of the stronger (lower) vortex or by decreasing the size of the weaker (upper) vortex. In this sense, according to Professor H. Zickendraht, we have a new type of wing from which the boundary layer is removed by forcing air out or sucking it in through openings in the upper surface of the wing near its trailing edge.* (Fig. 3). This affects the lift and drag of the wing somewhat as follows.

An unsymmetrical wing, in an air current, is subjected, on its upper side, to a negative pressure and, on its lower side, to a positive pressure. The corresponding velocities v can be

*H. Zickendraht, "Magnuseffekt, Flettner-Rotor und Düsenflügel," Schweizer. Techn. Zeitschrift, 1926, No. 48, p.837 and No. 49, p.855.
H. Zickendraht and K. Wieland, "Propriétés aérodynamiques de surfaces portantes munies d'ajutages," Archives des sciences phys. et nat. de Genève, 1926, 5th Période, Vol. 8, p.145.

found from the Bernoulli equation

$$p - \frac{1}{2} \rho v^2 = \text{constant}$$

The velocity v of the flow on the upper side is increased to v' by the outflowing jets of air w at P (Fig. 2), accompanied by an increase in the circulation. Moreover, the air jets carry away or greatly diminish the upper obstructive vortices and thus increase the lift. On the other hand, the compressed air flowing from the openings with the velocity w must exert a reaction pressure P on the wing, as expressed by the equation

$$P = \rho q w^2$$

in which q represents the total cross section of all the openings. This pressure therefore reduces the drag. The experiment confirmed both the increase in lift and the decrease in drag.

Some time ago similar experiments were undertaken by A. Lafay, who obtained a lift on wind rotors from whose surface layers of air were thrown off tangentially (Comptes Rendus 180, 1925, No. 16, p.1197, and No. 18, p.1901). Furthermore, the action of slotted wings was demonstrated ("Untersuchung an Handley-Page-Flügel," Zeitschrift für Flugtechnik und Motorluftschiffahrt 12, 1921, p.161; "Spaltflügel-Flugzeuge," Zeitschrift des Vereines Deutscher Ingenieure 19, 1927, p.645).

Apparatus

The poplar wing model had the dimensions shown in Figure 3. The diameter of each of the five tubes was 1.8 mm (0.07 in.). This wing model was secured to the air-resistance mechanism invented by Professor H. Zickendraht, which rendered it possible to read the lift and drag directly in grams. (For a detailed description of the apparatus, see Ann. d. Phys. (4) 35, p.47, 1911).

The air stream was produced by a three-bladed fan which, with a 220 volt tension, gave a maximum air velocity v of 7.6 m (24.9 ft.) per second, as determined by means of a Pitot tube and Toepler level. The compressed air for the jets came from the pressure chamber of a piston air pump. With regard to the tightness of the rubber delivery tubes, an overpressure of 1 atm. was found to be the maximum admissible limit. The pressure b was read on a mercury manometer (Fig. 4).

A Pitot tube, which was placed immediately opposite one of the openings (Fig. 4), in combination with an open water manometer (instead of the Toepler level, whose range was too small), gave the velocity w of the outflowing air jet according to the equation

$$w = \sqrt{\frac{2\,g\,h\,\rho'}{\rho}}$$

in which $g = 981\ g \times cm/s^2$; h represents the manometer height, ρ' (water density) = 1/g, and ρ (air density) = 0.0017/g.

At an overpressure b of 0.84 atm., the following jet velocities w were obtained:

Jet	1	2	3	4	5
h (cm)	21.6	35.2	32.2	22.0	23.4
w (m/s)	60.2	76.8	73.5	60.7	62.7

Mean: w = 66.8 m/s (219 ft./sec.) at b = 0.84 atm.

In the following, the pressure b was measured in atmospheres, from which the jet velocity w was easily calculated

$$w = \sqrt{\frac{b}{0.84}}\, 66.8 \text{ m/s.}$$

Performance of Experiments

1. Lift A and drag W of the wing in terms of the air-flow velocity v

Four curves were plotted, namely, for the angles of attack (α°) 0° and 10°, for the jet velocities (w) 0 and 72 m/s (b = 0.97 atm.).

TABLE I.

v m/s	A g	W' g	W g	α°	w m/s
0.0	0.0	0.0	0.0	0°	0
4.5	3.7	2.0	0.5		
6.6	8.95	3.7	0.7		
7.5	11.9	4.6	0.6		
0.0	0.0	0.0	0.0	10°	0
4.5	8.95	3.3	1.8		
6.6	20.0	7.0	4.0		
7.5	25.4	8.95	5.0		
0.0	0.0	-7.0	-7.0	0°	72
4.5	6.1	-3.5	-5.0		
6.6	11.65	-1.2	-6.6		
7.5	14.0	0.2	-3.8		
0.0	0.0	-7.0	-7.0	10°	72
4.5	11.9	-2.5	-4.0		
6.6	23.5	1.8	-1.2		
7.5	28.6	3.9	-1.0		

The numbers in the W' column represent the uncorrected drag values of the wing, from which the drag values of the wing support are to be subtracted. For the wing support alone the following values were obtained at various velocities v.

v (m/s)	0.0	4.5	6.6	7.5
A (g)	0.0	0.0	0.0	0.0
W (g)	0.0	1.5	3.0	4.0

No improvement can therefore be made in the lift, while the wing drag must be reduced by the corresponding drag of the wing support. In what follows, the uncorrected drag will always be represented by W' and the corrected drag by W. The numbers in Table I are plotted graphically in Figures 5 and 6.

For $v = 0$ the negative drag W_0 must equal the reaction pressure P of the outflowing air jet

$$\underline{P = \rho\ q\ w^2 = 7.9\ g}$$

when

the air density = 0.00117 g (at 20°C and 740 mm Hg) = 1.2×10^{-6} g/cm³;

the jet velocity w = 7200 cm/s;

the nozzle cross section $q = 5\pi\ r^2 = 0.127$ cm²
(r = 0.09 cm).

From Table I we take the value $W_0 = -7$ g at w = 72 m/s and $\alpha = 0°$. The moderate agreement between P and W_0 shows, however, that the velocity measurement at the openings, whose diameter is scarcely greater than that of the Pitot tube (0.18 cm as against 0.15 cm), is admissible. Otherwise P would have to be smaller than W_0.

2. Lift and drag in terms of the angle of attack α at the constant air-stream velocity v = 7.5 m/s (24.6 ft./sec.). The drag values W' must therefore be uniformly reduced by 4 g (0.009 lb.).

Two experiments were tried, namely, at jet velocities of $w = 0$ and w = 70.5 m/s = 231.3 ft./sec. (b = 0.93 atm.).

TABLE II.

v = 7.5 m/s (24.6 ft./sec.)

w = 0 m/s				w=70.5 m/s (231.3 ft./sec.)			
α°	$\frac{A}{g}$	$\frac{W'}{g}$	$\frac{W}{g}$	α°	$\frac{A}{g}$	$\frac{W'}{g}$	$\frac{W}{g}$
0°	11.9	4.6	0.6	0°	14.0	-0.5	-4.5
2°	14.25	6.4	2.4	2°	17.1	-1.0	-5.0
4°	17.1	6.9	2.9	4°	20.2	-0.6	-4.6
6°	19.95	7.7	3.7	6°	23.5	0.4	-3.6
8°	22.4	8.4	4.4	8°	26.8	1.4	-2.6
10°	24.85	9.0	5.0	10°	29.4	2.0	-2.0

The curves are plotted in Figure 7.

3. Lift and drag in terms of the jet velocity w at the air stream velocity $v = 7.5$ m/s (24.6 ft./sec.). Only the corrected values $W = W' - 4$ g are given in Table III. For five different angles of attack ($\alpha = 0, 6, 10, 15$ and 20°) two series of curves were plotted, one (as hitherto customary) for blowing out (jet velocity) and the other for sucking in (suction velocity).

TABLE III.

v = 7.5 m/s (24.6 ft./sec.)

w m/s	α=0° A g	α=0° W g	α=6° A g	α=6° W g	α=10° A g	α=10° W g	α=15° A g	α=15° W g	α=20° A g	α=20° W g
Jet velocity (+b)										
0.0	10.85	1.5	19.1	3.3	24.9	5.1	31.7	7.7	36.3	10.9
23.0	11.6	1.0	19.5	2.6	25.5	4.8	32.7	7.6	37.1	10.6
37.2	12.2	0.4	19.8	2.0	26.1	4.3	33.3	7.0	38.5	10.2
45.0	12.6	-0.4	20.0	1.4	26.2	3.1	33.7	6.3	39.4	10.0
50.5	12.7	-1.3	20.7	0.5	26.6	2.5	33.8	5.5	39.8	8.8
58.5	12.8	-2.5	21.3	-0.3	27.6	1.7	35.3	4.7	40.6	8.2
66.8	13.3	-4.5	22.4	-2.5	28.3	-0.4	36.4	2.7	42.5	6.7
Suction velocity (-b)										
-0.0	11.3	1.7	19.2	3.5	25.1	5.1	31.7	7.7	36.5	10.7
-23.0	12.8	1.9	20.6	4.0	26.1	5.6	32.5	8.1	38.1	11.3
-37.2	13.5	2.1	21.2	4.1	26.2	5.7	32.7	8.4	38.2	11.4
-45.0	13.6	2.0	20.9	4.1	26.3	5.8	32.8	8.5	38.0	11.5
-50.5	13.6	2.2	20.9	4.3	26.5	5.9	32.9	8.7	38.4	11.7
-58.5	13.6	2.2	20.8	4.2	26.5	6.0	32.8	8.7	38.3	11.7
-66.8	13.9	2.3	21.2	4.3	26.2	5.9	32.9	8.7	38.3	11.6

Note.- The first number series of +b and -b must, of course, agree perfectly with one another, if correctly measured. Any discrepancies are chiefly due to inaccurate reading of the angle of attack.

The curves are plotted in Figure 8.

At the suggestion of Professor Prandtl, the calculated induced drags W_d (Cf. Fuchs and Hopf, Aerodynamik, "Handbuch der Flugzeugkunde," Volume II, p.106 ff) were compared with the experimentally found values in Table III. The total drag W was measured, for which, with normal wings (without jets), we have $W = W_d + W_p$ (the profile drag). The induced drag was calculated on the assumption of an elliptical lift distribution along the span l as

$$W_d = \frac{A^2}{\pi\ p\ l^2}$$

in which A is the lift, $p = \frac{\rho}{2} v^2$ the dynamic pressure and l the wing span. For $\rho = 1.2 \times 10^6$ g/cm³, v = 750 cm/s and l = 12 cm, we have, in the C.G.S. system,

$$W_d = \frac{A^2}{152.6}\ g \quad \text{(g in grams weight).}$$

In the flow of the compressed air jets, the reaction W_r opposes the normal drag $(W_d + W_p)$, so that the total drag W equals $W_d + W_p - W_r$. The reaction is calculated, according to the equation, as $W_r = P = \rho\ q\ w^2$. For $q = 5\ \pi\ r^2 = 0.127$ cm² and the above value of ρ, we have

$$\underline{W_r = 0.1524 \times 10^{-6}\ w^2\ (g).}$$

When the air is sucked in through the openings, there is no reaction in the opposite direction, which would generally give negative values for the profile drag according to the equation $W = W_d + W_p + W_r$. This is not sensible, however. On the contrary, we obtain sensible values for W_p throughout by assuming that the reaction can be disregarded when the air is sucked in. We then have simply $W = W_d + W_p$, the same as for a normal wing.

On the basis of Table III, we will now investigate as to how far the induced drag and the profile drag are affected by the flow of air through the openings. This purpose is served by

Table IV, in which the values of W, w, and A were taken from Table III, while the values of W_d and W_p were accurately calculated to two decimal places by the above formulas. W_p was then found to be $W + W_r - W_d$ when the air was expelled through the openings and $W - W_d$ when it was sucked in through them.

TABLE IV.

$w^2 \times 10^6$	W_r	Air blown out (+b)				Air sucked in (-b)				α^0
		A^2	W	W_d	W_p	A^2	W	W_d	W_p	
0.00	0.0	117.7	1.5	0.8	0.7	127.7	1.7	0.8	0.9	0°
5.29	0.8	134.6	1.0	0.9	0.9	163.8	1.9	1.1	0.8	
13.84	2.1	148.8	0.4	1.0	1.5	182.2	2.1	1.2	0.9	
20.25	3.1	158.8	-0.4	1.0	1.7	185.0	2.0	1.2	0.8	
25.50	4.0	161.3	-1.3	1.1	1.6	185.0	2.2	1.2	1.0	
34.22	5.2	163.8	-2.5	1.1	1.6	185.0	2.2	1.2	1.0	
44.62	6.8	176.9	-4.5	1.2	1.1	193.2	2.3	1.3	1.0	
0.00	0.0	364.8	3.3	2.4	0.9	368.6	3.5	2.4	1.1	6°
5.29	0.8	380.3	2.6	2.5	0.9	424.4	4.0	2.8	1.2	
13.84	2.1	392.0	2.0	2.6	1.5	449.4	4.1	2.9	1.2	
20.25	3.1	400.0	1.4	2.6	1.9	436.8	4.1	2.9	1.2	
25.50	4.0	428.5	0.5	2.8	1.7	436.8	4.3	2.9	1.4	
34.22	5.2	453.7	-0.3	3.0	1.9	432.6	4.2	2.8	1.4	
44.62	6.8	501.8	-2.5	3.3	1.0	449.4	4.3	2.9	1.4	
0.00	0.0	620.0	5.1	4.1	1.0	630.0	5.1	4.1	1.0	10°
5.29	0.8	650.3	4.8	4.3	1.3	681.2	5.6	4.5	1.1	
13.84	2.1	681.2	4.3	4.5	2.1	686.4	5.7	4.5	1.2	
20.25	3.1	686.4	3.1	4.5	1.7	691.7	5.8	4.5	1.3	
25.50	4.0	707.6	2.5	4.6	1.9	702.3	5.9	4.6	1.3	
34.22	5.2	761.8	1.7	5.0	1.9	702.3	6.0	4.6	1.4	
44.62	6.8	800.9	-0.4	5.2	1.2	686.4	5.9	4.5	1.4	

Table IV (Cont.)

$w^2 \times 10^6$	W_r	Air blown out (+b)				Air sucked in (-b)				α^o
		A	W	W_d	W_p	A	W	W_d	W_p	
0.00	0.0	1005	7.7	6.6	1.1	1005	7.7	6.6	1.1	15°
5.29	0.8	1069	7.6	7.0	1.4	1056	8.1	6.9	1.2	
13.84	2.1	1109	7.0	7.3	1.8	1069	8.4	7.0	1.4	
20.25	3.1	1136	6.3	7.4	2.0	1076	8.5	7.0	1.5	
25.50	4.0	1142	5.5	7.5	2.0	1082	8.7	7.1	1.6	
34.22	5.2	1246	4.7	8.2	1.7	1076	8.7	7.0	1.7	
44.62	6.8	1325	2.7	8.7	0.8	1082	8.7	7.1	1.6	
0.00	0.0	1318	10.9	8.6	1.3	1332	10.7	8.7	2.0	20°
5.29	0.8	1376	10.6	9.0	2.4	1452	11.3	9.5	1.8	
13.84	2.1	1482	10.2	9.7	2.6	1459	11.4	9.6	1.8	
20.25	3.1	1552	10.0	10.2	2.9	1444	11.5	9.4	2.1	
25.50	4.0	1584	8.8	10.4	2.4	1474	11.7	9.7	2.0	
34.22	5.2	1648	8.2	10.8	2.6	1467	11.7	9.6	2.1	
44.62	6.8	1806	6.7	11.8	1.7	1467	11.6	9.6	2.0	

The behavior of the induced drag (increase with increasing angle of attack and increasing flow of air through the openings) is no longer surprising, since its course must be proportional to the square of the corresponding lift. The profile drag is only slightly affected by the angle of attack, so long as it is not excessive (up to 15°). Neither is it very greatly affected by the air flow through the openings in either direction. The expelled air produces a maximum value of the profile drag in the vicinity of $w = 45$ m/s (148 ft./sec.), which is about twice the original value (at $w = 0$). The suction air, on the contrary, produces no such maximum, but only a slight increase in the profile drag with increasing velocity w.

C o n c l u s i o n s

From Figures 5 and 6, it is seen that the percentage increase in the lift of a wing resulting from the air velocity w (i.e., the ratio of A with w to A without w) is considerably less favorable for 10° angle of attack than for 0°. Furthermore, it is found that this ratio with increasing air speed approaches the value 1. When we consider that an air-stream velocity of 7.5 m/s (24.6 ft./sec.) signifies very little in actual flight, any practical evaluation of a wing, from which the boundary layer is removed by pressure or suction, does not appear very promising.

For the present, the principal value of the whole problem is probably theoretical. Doubtless, systematic experiments with such wings will help considerably to clarify the theory of vortex liberation. To me the first indication in this direction appears to be the different behavior of the wing lift in the outflow and inflow of air through the wing openings (Fig. 8). The fact that, with the outflowing air jets, the lift continually increases (so far as it has been measured) with increasing pressure $(+b)$ and that, with the inflowing air on the other hand, after an initial increase, it does not exceed a certain limit even at very small pressures $(-b)$, must have something to do with the nature of the vortex formation at the trailing edge. This phenomenon may very likely be due to the fact that the effect of the air jets, in the sense of the previously mentioned Zickendraht conception, is a double one (decrease in turbulence and increase in velocity) and that the air sucked into the tubes probably increases the lift only through its effect on the upper vortices. It is illuminative that, after the dissolution of these obstructing vortices, a further increase in the suction velocity does not increase the lift.

Very little can yet be concluded from the now available data. It will first be necessary to vary systematically the position, number and size of the openings in the wing. Furthermore, the introduction of disks at both ends of the wing is not only objectionless but produces even more favorable results.

In conclusion, I wish to express my best thanks to Professor Zickendraht, on whose ideas the present work is based, for his constant encouragement and assistance.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

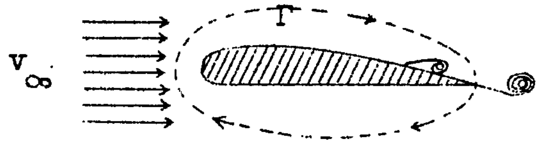

Fig.1 Compensating circulation with unsymmetrical vortex formation. Γ, circulation, v_∞ ,velocity of parallel flow.

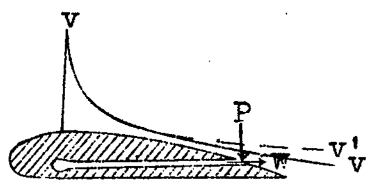

Fig.2 Velocity values according to the Bernoulli equation. P, reaction pressure at exit of jet.
w, exit velocity of air jets, v, velocity of air-flow on upper side of wing, v' increased velocity on upper side of wing.

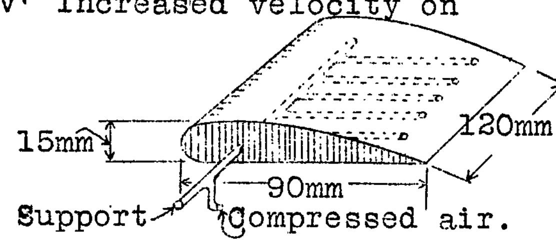

Fig.3 Poplar wing model with tubes.

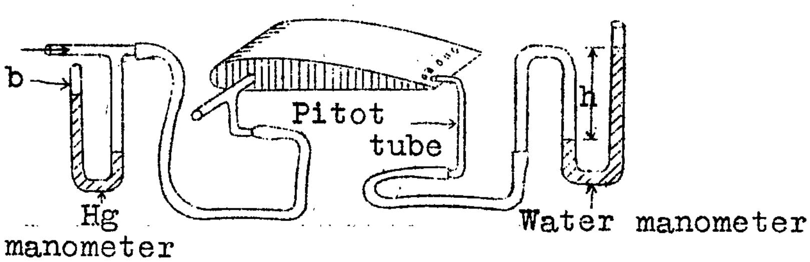

Fig.4 Experimental apparatus.b, over-pressure in manometer.

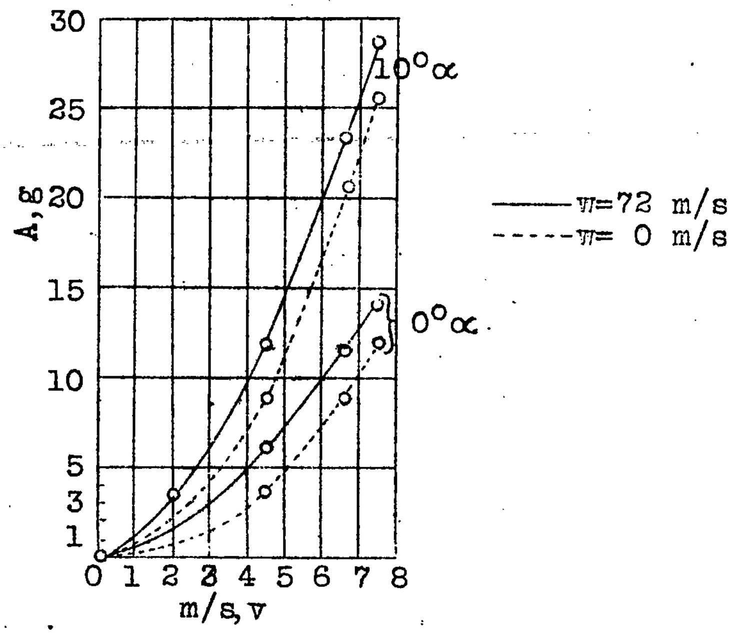

Fig.5 Graphic representation of the values given in Table 1.

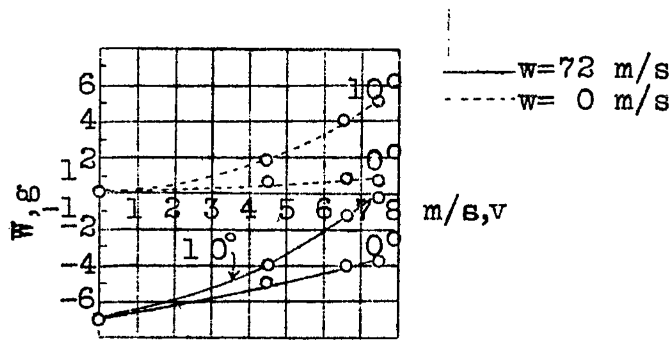

Fig.6 Graphic representation of the values given in Table I.

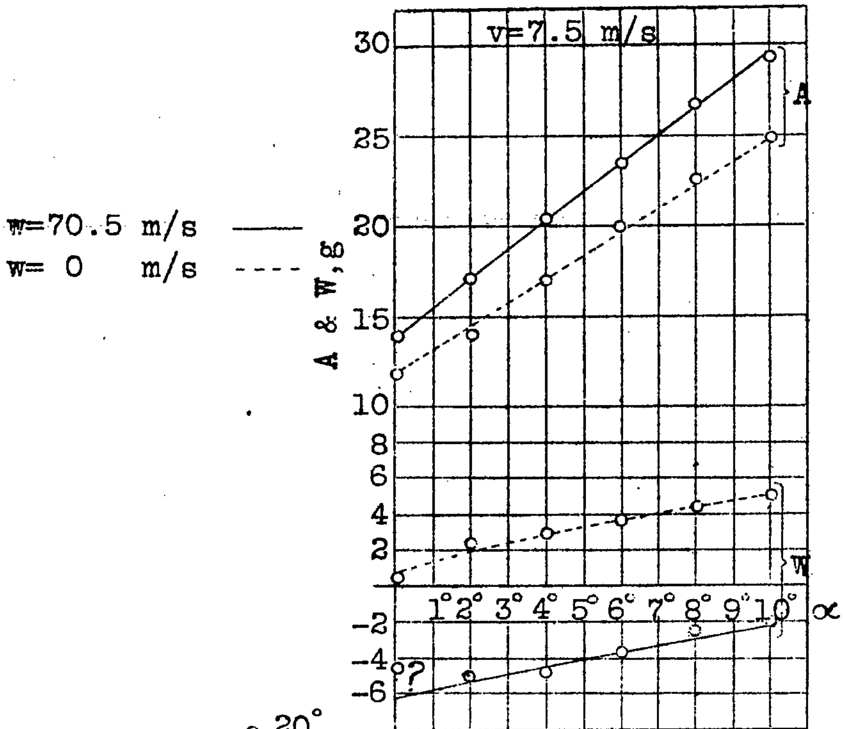

Fig.7 Graphic representation of values given in Table II.

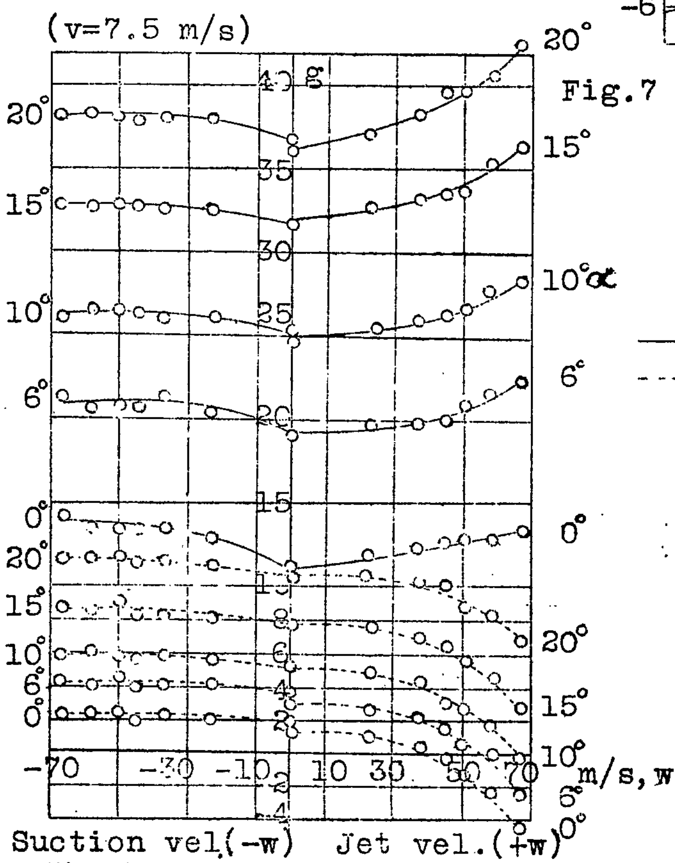

Fig.8 Graphic representation of values given in Table III.